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Plasma Wave Characteristics of the Jovian Magnetopause Boundary Layer: Can Wave-Particle Interactions Cause the Jovian Aurora?

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Abstract

The full Jovian magnetopause boundary layer (131.) plasma wave spectra from 1 ()”^{3} to 10^3 Hz, have been measured for the first time. For one intense event, the magnetic and electric spectra were 2 x 10^{-4} f$^{-2.4}$ n T^2/Hz and 4 x] 0^{-9} f$^{-2.4}$ V^2/m^2 Hz, respectively. The B'/E' rat io dots not have a f^{-1} dependency, so it is suggested that the waves are a mixture of whistler mode electromagnetic emissions and electrostatic waves. The 13’ and E' spectra are broad band with no obvious spectral peaks. The waves are sufficiently intense to cause cwss-field diffusion rapidly enough to create the BL itself. A Jovian 111, thickness of 10,700 km is predicted, which is consistent with past in-situ measurements. The superposition of a broad band B' and E' spectra and the spectral shape are quite similar to the BL waves at earth (however the Jovian waves are orders of magnitude less intense). It appears that the solar wind/magnetosphere dynamos at the two planets are similar enough to be consistent with a common physical mechanism for both.

The Jovian BL waves arc sufficiently intense to cause strong pitch angle diffusion for <5 keV electrons and] keV to] M c V protons. Using the measure d particle energy spectra, it is found that 0.85 ergs cm^{-2} s^{-1} can be contributed to the aurora from the 1 ()- 1 ()() keV proton energy range. If this energy spectrum is extrapolated to lower energies, an upper limit energy deposition from 1 keV to 1 MeV protons is 6.9 ergs/ct11^{2}s. The predicted energy deposition is similar to that measured by Hubble (8 ergs/cm2s), and the predicted ionospheric latitudinal width of-loo-200 km is quite similar as well, The con finement of the precipitating electrons to <5 keV is consistent with the low energy x-ray spect rum measured by the EINSTEIN and ROSAT satellites. Thus, it appears as if the Jovian BL waves and particles are sufficient to explain the location, latitudinal width and intensity of the high latitude aurora. The mechanism is essentially the sa me as for the Earth’s dayside UV aurora.

Introduction

Plasma waves present in the ːarth's magnetopause boundary layer 3L) are important fo·r several fundamental geophysical processes ·irst, they are products of plasma ins abilities associated with strong particle anisotropies and/or plasma and field gradients or are resonantly amplified magnetosheath Secondly, through resonant interactions with charged particles, they are important for momentum and energy transfer from the solar wind to the magnetosphere/ ionosphere. Concerning the first topic, that of a wave source, several instabilities/mechanisms have beeɪ discussed n the literature (Kennel and Petschek, 1966; ɔ'Angelo, 1973; Ashour-Abdalla and Thorne, 1977; Swift, 977; Huba et al., 1978, LaBelle and Treumann, 1988, Rezeau et al., 1989; ʒelmont et al., 995). However at this time there has been little agreement as to the specific mechanism(s). The broad-band nature of the waves with a lack of accompanying peaks (Gurnett et al., 979; Anderson et al., 982 Tsurutani et al., 1989) has made such identification extremely difficul The relative constancy of the power-law spectra over al local mes (Tsurutani et a 989) is another well established observat on. Assignment of specific instabi ities has had the difficulty in explaining both the broadband nature and the local time dependences. A recent model (Drake et al., 994), involving the current convection instability evolving to a strongly turbulent state seems very promising. lowever, only the electrostatic has studied thus far.

The magnetopause boundary layer waves have been speculated to be important for two different types of particle transport. The waves have been shown to be capable of diffusing solar wind/magnetosheath plasma onto closed (magnetospheric) field lines at a rate rapid enough to form the nagnetopause boundary layer itself (Tsurutani and Thorne, 982; Gendrin, 983). This can be hought of as a specific "viscous interaction" mechanism (Axford and Hines, 196 ; Cole, 96 ; Tsurutani and Gonzalez, 995), in which he solar wind flow energy is transferred to the magnetosphere. Secondly, rapid pitch angle scattering of energetic particles via cyclotron resonan interact ons with the waves can provide significant particle loss to the ionosphere to provide the source of the dayside aurora at ːarth (Tsurutani et al., 198 a phenomenon which is ever present and is independent of substorms.

A plasma boundary layer has been identified inside the Jovian magnetopause (Lanzerotti et al., 1979; Sonnerup et al., 1981; Scudder et al., 1981). Most recently, Phillips et al. (1993) has identified 14 crossings, using the Ulysses Jupiter flyby data. Tsurutani et al. (1993) reported the detection of electromagnetic waves at the proton cyclotron frequency at a limited number of these crossings. They have also determined the cross-field diffusion rate, using measured wave amplitud es and have shown them (() be sufficient to form the Jovian boundary layer. In fact, the calculated thickness is quite similar to that during Pioneer]() and 1 1 crossings when triple crossings were used to experimentally determine the spatial thickness (Sonnerup et al.,1981).

Galvin c1 al. (1993) using the Ulysses SWICS observations have identified ion species 01 both Jovian magnetospheric origin (O', O^{2+}, So-t, S^{3+}) and of sheath origin (He^{2}, high charge states of' CNO) within the BL. ions of magnetospheric origin arc also found within the Jovian magnetosheath. These observations clearly indicate that charged particle transport across the magnetopause boundary is occurring in both directions.

Previous mechanisms for the Jovian aurora that have been propo sed (Thorne and Tsurutani 1979; Thorne, 1981; T horne and Moses, 1983, Gehrels and Stone, 1983, Waite et al., 1983; Horanyi et al., 19S8; <'ravens et a]., 1 995) have depended on enhanced wale-par(ic]c interactions in and near the Io torus, localizing the aurora to 1, ≈ 6 to 17. The first observations of x-rays from Jupiter were mea sured onboard E INSTEIN by Metzger et al. (1983). Soft x-rays (0.2 - 3.0 keV) were reported to have been detected from both polar regions. Arguments were presented that the x-rays were not electron gene rated bremstrahlung, but line emissions associated with precipitating from 0 and S ions with energies between 0.03 and 4.0 MeV/nucleon. More recent observations by Waite c(al. (1994) using the ROSA']' satellite have arrived at similar conclusions. One difficulty in this scenario is that the same mechanism cannot be used to prod uce the bulk of the UV aurora, and a different mechanism must be derived for the latter. Another problem is that more recent observations have placed the aurora at considerably large L values (Dols c1 al.. 1992; (itl'dl'(let al., 1993), opening up the possibility that the aurora may not be related to the plasma torus at all, but might be associated with phenomena occurring on higher latitude field lines.

The purpose of this paper is two-fold. First, wc will examine all 14 of the Phil lips et al. (1993) Jovian boundary la yer crossings to characterize for the first time E' and B' wave spectra within this region of space. For the magnetic field, wc will combine the d.c. magnetometer and a.c. search coil data sets to get an exte nded spectra from d. c. to ELF frequencies. Wc will also examine the electric field spectra. These E' and B' spectra will be compared and contrasted to those at the Earth's boundary layer to determine the commonality/lack of commonality of the wave properties at the two different planetary magnetospheres. This important information will give constraints for any (common) mode] of wave generation. The ratio of E' and B' will be used to determine how m uch of the sp ectra is due to electromagnetic waves and how m uch is electrostatic (see discussion in Gurnett et al., 1979).

Secondly, using the measured wave power and measured energetic particle flux within the Jovian boundary layer, the pitch angle diffusion rates and particle losses into the Jovian ionosphere will be calculated using the Kennel-Petschek (1966) expressions. These precipitation rates and the location of the precipitation will be discussed in light of recent Hubble observations of the Jovian aurora (Dols, et al. 1992; Gérard et al., 993; Rego et al., 1994; Prange, 1995)

With energetic particle measurements from several different experiments onboard Ulysses, we wil determine the precipitation fluxes. These will be compared with the measured UV and x-ray luxes measured by other spacecraft

Method of Analyses

The Ulysses magnetometer experiment is described in Balogh et al. (1992). The vector helium sensor portion of this instrument has a temporal resolution of one vector s^{-1}, the resolution used in his study. The Ulysses Radio and Plasma (URAP) instrument is described n Stone et al. (1992 . There are 10 low-band and 12 high-band channels. The low-band channels extend from 0.22 to 5.3 Hz and the high-band from 9.3 to 448 Hz. For the high-band channels, electric and magnetic fields are measured perpendicular to the spin axis, called E_x and B_y. Data from he URAP and magnetometer instruments have been merged to form a continuous spectrum in B'. The URAP E' data is used for the electric part of the spectrum.

The HI-SCALE (Heliosphere Instrument for Spectra, Composition and Anisotropy at Low Energies) consists of 5 detector apertures in wo separate telescope assemblies which form different angles with the spacecraft spin axis (Lanzeroti i et al., 1992 HI-SCALE is able to measure electrons with energies between 40 and 300 keV in 4 different channels and ions (Z3 with energies between 50 and 5000 keV (assuming protons) in 8 different channels.

The five detectors are identified as LEMS30, LEFS60, EMS120, LEFS150 and CA60. The numbers in the names indicate the orientation of the telescopes' central axes relative to the spin axis of he spacecraft During each 12s-rotation the measured ions and electrons are sampled into 4 (LEMS30, LEFS150) and 8 sectors (LEMS120, LEFS60, CA60), respectively. The HI-SCALE instrumen provides measurements from 32 various directions in space with a high time resolution of 12 or 24s. More detailed information about the instrument can be found in Lanzerotti et al. (1992).

The Jovian boundary layer waves are analyzed for the periods indicated by Phillips et al. (1993). The density, temperature and distribution function signatures are the most reliable ones for the identification of the start and stop times for the boundary layer (at Jupiter). All fourteen intervals of the inbound (~1 local time) and outbound passes (~18 local time) have been studied

Results

Waves

'able duplicated from Phillips et a 993) gives the fourteen time intervals for the Ulysses Jovian boundary ayer (3 .) crossings. These ntervals were identified using the plasma density and velocity characteristics alone. For the B . intervals, quantities from both of three parameters were intermediate between those of the magnetosheath and magnetosphere. From left to right, the columns are: the event number, the type of transition, the entry time and the exit time. There are five crossings on the inbound pass, days 33-35, 1992, and nine crossings on the outbound pass (days 43-45, 1992). Throughout the paper, we will use the event numbers (listed chronologically) rather than the dates, to save space.

Figure 1 gives an overview of the low frequency E' and 3 waves for all fourteen 3 events. From top to bottom are: the :' spin plane average 9.3, 14, 19 and 28 Hz channel wave intensities, the B spin plane average wave intensities for the same frequency channels, the B' ninute and 10 minute variances (taken from the d.c. magnetometer), and the spacecraft location relative to the planet. The shaded intervals are the Phillips et al. designated BL intervals. Bow shock crossings are indicated by vertical dashed lines. The magnetosheath/BL intervals are given by solid horizontal bars in the top panel.

Several features are readily apparent from the Figure. Above background wave intensities are sometimes present in frequency cha nels ranging from 9.3 Hz (displayed), up to the electron cyclotron frequency. When present, the enhanced signals are most noticeable in the lowest frequency channels shown. Although there are similar la ge wave amplitudes in the magnetosheath region (nonshaded intervals indicated by horizontal bars), the magnetosheath signals are generally less intense than those in the boundary layer. This is similar to the situation for the Earth's BL/magnetosheath waves (Gurnett et al., 1978; Anderson et al., 1982).

The B' wave intensities are considerably different. Typically, the magnetosheath and boundary layer intervals are quiet (near instrument backg ound) in ELF/VLF magnetic fluctuations, especially for the inbound pass. However, on the outbound pass for days 43 and 44, and also the beginning of day 45, the and magnetosheath ELF wave intensities were noticeably more ntense. The waves were most prominent in the lowest frequency channels (see the 9.3 and 14 Hz channels).

The 1 min and 10 min variances derived from the 1 -s magnetometer data were also low on the inbound pass, but considerably more intense on the outbound pass. The variance values were highest on the outbound pass on day 43. The magnetosheath values on this day were high as well.

The interplanetary plasma conditions were considerably different on the inbound pass than on the 01111)0111)(1 pass, On the inbound pass, the velocity and density were 510 km/s and 0.07 cm^{-3} and on the outbound pass they were 395 km/s and ().3 cm^{-3} (Phillips, private comm., 1995). Due to the unusually low ram pressure during the inbound pass, the magnetosphere was greatly extended at encounter (Smith and Wenzel, 1993). The solar wind ram pressure was more normal during the 011[[D[ )111)(] pass. From the wave measurements, it is clear that the ram pressure has a direct effect on BL wave intensities (in comparison, only the magnetoshe ath B_z had an effect on wave intensity at Earth; Tsurutani et al., 1989).

Figure 2a illustrates the power spectra for the magnetometer data for all fourteen BL intervals. Each spectrum has been fitted to a power law and is shown in Figure 2b. All of the spectra are similar in shape, varying primarily in intensity. The most intense intervals (events 8, 9 and 10) are over one order of magnitude greater in intensity than the average. These latter events are called out in Figure 2b.

Figure 3 illustrates the URAP B' ELF wave power spectra for the 14 BL intervals. Almost all events are at or near instrument till'csllol(ll c\Jcls,cxcc])t near a narrow frequency range from 1-10 117. The two different instrument background levels noted from 20-400 Hz are due to the instrument mode selection (some instrument self-illtcll'clctlcc).

Since the day 43 events are the most significant in terms of wave intensity, we will focus our attention on these events, particularly on event numbers 9 and lo. The E' and B' spectra for event numbers 9 and 10 (day 43) are shown in Figures 4 and 5, respectively. The electric wave spectra are given in the left-hand panels. The instrument background is also shown. The E' spectra have a $1.2 \times 10^{-9} f^{-2.3}$ V^2/m^2 Hz fil and a $4.1 \times 10^{-9} f^{-2.4}$ V^2/m^2 Hz fit for the two intervals, respectively. The spectra are broadbanded with no obvious peaks within the frequency range examined. The event 10 spectrum is higher across the whole frequency range than the event 9 spectrum. Event 10 also has a spectral shape that is independent from that of the background curve, indicating that the natural wave power is dominating the spectrum.

'he ELF B' spectra for events 9 and 10 are shown n the right-hand panels of Figures 4 and 5. 'he signals are above instrument background in the range from Hz to 10^2 Iz. The power law its to these two events are .8 x 0^{-4} $f^{2.2}$ and 3.5 x 10^{-4} $f^{2.5}$ nT^2/I z, respectively The wave intensities were greatest at the very beginning of the two events. One minute averages of his portion of the BL crossings were generated and are indicated as "B_{max}" curves.

The magnetic spectra at lower frequencies (2 x 0^{-3} to 5 x 10 Iz) were given in Figure 2a and 2b. This is obtained from the vector helium magnetometer which has an instrument noise level that is independent of frequency. This level is indicated. Note hat the shapes of the two power spectra are remarkably similar to that determined for the higher frequency JRAP data.

The spectra can be fitted together by extrapolating the d.c magnetometer power spectra to the higher ELF frequencies of the URAP experiment Th is s shown by dashed lines in Figures 6a and b. Thus, the wo curves join smoothly together at ~1.0 Hz as expected the sensitivity of d.c. magnetometers and search coils become comparable at ~1 Hz). The part of the search coi curve for 'requencies below this level are purely instrument noise.

If one makes a fit to the overall combined magnetic spectra, we get 2.4 x 10^{-4} $f^{-2.2}$ nT^2/Hz and 1.8 x 10^{-4} $f^{2.4}$ nT^2/Hz, respectively. It is interesting to note that the frequency dependences on the power spectra for E' and B' are similar. More will be commented on this feature somewhat later

To determine if the broadband BL waves are purely electromagnetic or instead are a combination of both electromagnetic plus electrostatic waves, we calculate the E'/B' ratio as taken from event 10, an interval of day 43 where the wave amplitudes were the highest. The results are given in Figure 7. At 1 Iz, B'/E' ~200. The ratio decreases with increasing frequency, but then increases from (Iz to above 10^2 Hz. Overall, the ratio has a relat vely constant value near 00.

For purely electromagnetic waves, B'/E' = n = c/V_{ph}, where n is the index of refraction, c, the velocity of light, and V_{ph} he phase velocity of the wave. 'or electromagnetic waves at frequencies above the proton cyclotron frequency, these would be whistler mode waves (right-hand polarized). At low frequencies, V_{ph} is ~V_A, the Alfvén velocity. At higher frequencies, n will decrease with a f^{-1} dependence. From measured values of B_o (5 x 10^{-5} G) and ρ (≈ 0.1 cm^{-3}), we find V_A = 3.4 x 10^7 cm s^{-1} and n ≅ 870.

'he measured value of B'/E' s reasonably close to the theoretical value, given the errors in he measurements of B' and E'. Iowever, there is no f^{-1} dependence on the value, except for perhaps for the narrow frequency range 10^{0}-1 01'17,. Thus, we conclude that the Jovian BL waves must be a mixture of whistler mode plus electrostatic waves. This is the same conclusion that was reached for the Earth's BL waves (Gurnett et al., 1979). We should mention that Rezeau et al. (1989) and Belmont et al. (1995) have interpreted these fluctuations are convected low frequency Alfvén waves. Our results are not inconsistent with this picture. However, for the remainder of the paper we will assume the former interpretation and will make conclusions based on (his assumption.

Boundary Layer Formation and Thickness

The boundary layer thickness due to cross-field diffusion of magnetosheath plasma can be calculated assuming resonant wave-particle interactions (Eviatar and Wolf, 1968; Tsurutani and Thorne, 1982), using the measured wave-particle interactions discussed previously. This same diffusion process will allow the escape of energetic magnetospheric ions into the magnetosheath and into interplanetary space as well.

The cross field scattering rate is:

$$D_{\perp,B'} \approx 2\,(B'/B_o)^2 D_{max} \qquad (1)$$

where B_o is the ambient magnetic field and D_{max} is the maximum or Bohm diffusion rate. D_{max} is given by:

$$D_{max} = E_{\perp} c/2eB_o = 5 \times 10^5\ E(keV)/B_o\ (nT)\ km^2\ s^{-1} \qquad (2)$$

where $E_{\perp}$ is the perpendicular kinetic energy of the particle. At the Jovian boundary layer, $B_o \approx$ 5 nT. Assuming a magnetosheath proton energy of 1 keV, D_{max} is 10^5 km^2 s^{-1}. Using a magnetic wave power of $B'^2 \approx 10^{-1}$ 11'1'', we get $D_{\perp,B'} \approx 10^3$ km s'', For the time scale of cross field diffusion, wc use the convection of magnetosheath plasma from the magnetopause nose to the dawn/dusk flank. A sheath velocity of 100 km s^{-1} and a distance of I 50 R, are assumed. We find the BL thickness is predicted to be 10,700 km or -().15 R_J thick. From analyses of a triple crossing of a Pioneer 10 triple crossing of the magnetopause/plasma boundary layer, Sonnerup et al. (1981) determined a thickness of 9,100 to 13,()()() km. This measurement is in excellent agreement with the above theoretical expectations.

Pitch Angle Diffusion

The effects of both the E' component and the B' component of the waves should be analyzed and discussed in terms of effectiveness for pitch angle scattering rates We use the expression:

$$D_{\alpha\alpha}^{\pm} \sim (B'/B_o)^2 2\pi f_g^{\pm} \eta \quad (3$$

$$D_{\alpha\alpha}^{\pm} \sim (c / v)^2 (E'/B_o)^2 f_g^{\pm} \eta \quad (4$$

taken from Kennel and Petschek (966). n the above expressions, $D_{\alpha\alpha}$ is the diffusion rate due to resonance with electromagnetic waves (3) and with electric waves (4) , respect vely, f_g the particle gyrofrequency and η the fractional amount of ime hat the particle is in resonance with the waves. V is the particle velocity. rom measurements, we determine $f_e \approx 140$ Hz and $f_p \approx 7.6 \times 10^{-2}$ Hz.

To determine B' at cyclotron resonance, we assume first-order resonance:

$$\omega \quad \vec{k} \cdot \vec{V} = \Omega^{\pm} \quad (3$$

Assuming that he waves are whistler mode (right-hand polarized), the electrons will interact via the ordinary Doppler-shifted resonance condition

$$\omega + k_{\|} V_{\|} = \Omega \quad (4)$$

giving:

$$\omega = (eB/mc)/(\; + V_{\|}/V_{ph}) \quad (5)$$

Using representat ve energies of keV o 1 MeV for he particles, we have calculated e frequencies. These values, the electromagnetic wave power, diffusion ates and pitch angle scatte ng rates are given in Table 2. Assuming a conservative) field line at =60, the particle bounce times are calculated. By comparing $T_{\alpha\alpha}$ to T_{bounce}, we determine if the par icles are on strong or weak pitch angle diffusion.

The 1 keV electrons are found to be on strong diffusion, while the 10 keV electrons are on near-strong to weak diffusion. Higher energy electrons are on weak diffusion.

The protons are a different story. Assuming that the electromagnetic wave power at frequencies above the proton cyclotron frequency is whistler mode, then the interaction of protons or ions with these waves will be through an anomalous Doppler-shifted cyclotron resonance where the particles overtake the waves. The first order resonance can be expressed as:

$$\omega - k_{\parallel} V_{\parallel} = \Omega^{+} \quad \textbf{(6)}$$

giving

$$\omega = (eB/m^{+}c)\,(1 - V_{\parallel}/V_{ph}) \quad (\text{-l})$$

Calculations similar to those for resonant electrons are given in the Table. The 1-10 keV])1'0101)s are on near-strong diffusion and the 10 keV and greater en ergy protons are on strong di ffusion. The diffusion rate is higher for the more energetic particles because the higher the particle energy, the lower tile resonant frequency. Because the waves have a power law dependence, the higher wave power at lower frequencies leads to greater di ffusion rates.

W C have also examined the pitch angle diffusion rates due to cyclot ron resonance with electrostatic waves. Wc find tile di ffusion rates for 1 keV protons are quite rapid and these particles are on strong diffusion due to this interact ion.

From the analyses of the pitch angle di ffusion rates due to both the whistler mode noise and the electrostatic waves, 1-5 keV electrons and 1 ke V to 1 Me V protons arc on strong di ffusion. Lower energy, < 1 keV plasma will also be on strong diffusion, but wc do not yet have accurate flux va lues, so the energy deposit ion from th ese particles cannot b e calculated at thi s time. We have also assumed that the ions are protons, for representative calculations. If heavier ions are present in the BL, their precipitatio n rates can be calculated in the sa me manner.

Figures 8 and 9 are the electron and ion spectra, respectively. The count rate from several detector heads (pitch angles) are given in each figure. The count rates are n early the same, indicating that the pitch angle distribution is nearly isotropic. This is in accord with the previous estimated strong pitch angl e di ffusion.

An exponential fit to the electrons is shown. Thi s is a conservative approximation and limits the particle energy at the low energy end. The protons are fit by a power law approximation. This seei ns to be a better fit than an exponential one. It should be reasonab ly accurate in the 10-100 keV range, but will be on the high-side for 1-10 keV energies. We are current ly looking into the accura cy Of these spectra.

Table 3 gives the energy deposition rate as a function of species and energy ranges. We find that the dominant energy is 10-100 keV protons. The energy deposition from this energy band is 0.84 erg cm^{-2} s^{-1}. It is possible that the energy from the 1-10 keV range could be substantial, perhaps even an order of magnitude higher. This will have to await further spectral analyses. We have also considered the possibility that these ions are sulphur or oxygen instead of protons. We cannot discriminate between these possibilities from the measurements. If they are sulphur or oxygen ions, the energy deposition rate from the ions will be more than an order of magnitude less.

The breakdown of the energy deposition as a function of particle species can be used as a prediction of the height and intensity distributions of the Jovian aurora. Similar studies were done for the Earth's dayside aurora with confirming ultraviolet spectral observations (Sivjee et al., 1982; Sivjee, 1983).

Imaging Observations

Energetic particles which have been pitch angle scattered into the atmospheric loss cone, follow the magnetic field lines down to the atmosphere of Jupiter where they impinge the atmospheric species and give rise to collisionally excited auroral emissions. For the major species in the Jovian atmosphere, atomic and molecular hydrogen, the resulting electronic transitions lie in the far ultraviolet (FUV) wavelength range.

The first Hubble Space. Telescope (HST) FUV images of the Jovian aurorae were taken during the fry-by of Ulysses, on February 7 and 9, 1992 with the Faint Object Camera (FOC). For these observations, the combination of the HST spherical aberration and non-optimal choices of wavelength ranges resulted in a moderate spatial resolution only (~0.2 -0.5 arcsec; i.e. ~700-~1500 km projected on the planetary disc). However, the basic morphology of the auroral emission derived from these observations was confirmed by the following observations which took place regularly about twice a year until the present (Gérard et al., 1993; 1994; Rego et al., 1995), including the last set of data obtained in July 1994 where the FOC had a much better spatial resolution after correction for telescope aberration (Prange et al., 1995). The brightest feature identified in the images is a very narrow oval which surrounds each pole at high latitude. The oval looks amazingly narrow and perfectly regular and continuous along tens of thousands of kilometers, although some very localized discrete emissions are superimposed (it looks much more regular than the terrestrial discrete auroral emission on the Earth's nights, This suggests that the precipitating particles originate from a well-defined and stable large-scale layer in the outer Jovian magnetosphere. In the case of the February 1992 images, correlation's with simultaneous Ulysses particles and field measurements have shown that the emissions were likely to originate from the footprint of magnetic field lines just at the equatorward edge of the polar cap, crossing the equatorial plane near about 40-60"1<, (Prange et al., 1 995).

The images obtained in 1994 provide for the first time an estimate of the latitudinal extend of the oval. The pixel size used is now 0.014 x ().()2S arcsec^2. The point spread function (PSFV) encircles for 50% of the energy at this wavelength within a radius of ().()5 arcsec, and for 1-l) sources, the transverse resolution reaches ≈ ().()3()-().()35 arcsec, i.e. ≈ 100-150 km on the planetary disc. This resolution exceeds by far the capabilities of any past or existing observations.

Figure 10 a) shows a plot across the oval in the southern hemisphere, integrated over 40 pixels along the oval. The background disc emission has been derived from another image where the oval is mainly hidden on the nightside. The excess emission, which consists of a peak surrounded by some diffuse emission on both sides, is due to auroral excitation. The peak is extremely narrow, 2.2 pixels FWHM, or 0.063 arcsec (Figure 1o). Taking into account the instrument spatial resolution, the resulting intrinsic width of the auroral emission drops to about ().()3 arcsec, corresponding to a 120 km auroral structure projected on the disc, i.e., about 200 km perpendicular to the magnetic field lines. This incredibly small value is an upper limit because it includes any curvature of the oval along the 5000 kill of the cut, and some remaining noise in th c data. The peak intensity corresponds to a brightness of ≈ 475 kR. Using model estimates of the energy conversion factor (Rego et iii., 1995), the peak energy input fill x from the magnetosphere in this segment of arc is about ().] watt n^{-2} (-().3 watt m^{-2}) when deconvolved from the spatial transmission function. Plots across a different part of the oval, or at different dates She\\" that the width of the arc may extend up to a few hundreds of kms at 1)10S1, with about the same peak value of ().2 -(),3 watt m^{-2} See).

The present identification of such a narrow region of intense precipitation defines a very specific magnetospheric layer as the origin of the particle losses. In this paper, we argue that this layer is the magnetopause boundary layer.

Summary and Conclusions

I. It has been shown that the Jovian BL waves have sufficient intensity to cross-field diffuse the Jovian magnetosheath plasma across the magnetopause to create the BL (Tsurutani et al., 1993). The predicted thickness is in agreement with in-situ measurements (Sonnerup et al., 1981).

2. A comparison of the Jovian BL plasma wave spectra and the Earth's BL plasma wave spectra is given in Table 4. The electric field spectral shape is similar to the terrestrial counterpart. The terrestrial wave magnetic field component is highly variable, depending on the study. However, the Ulysses measurements are within the range of the spectral shapes reported in the terrestrial wave studies.

3. It should be noted that the Jovian BL wave amplitudes are considerably smaller than those at the Earth. In general, they are orders of magnitude smaller (Table 4). This should be noted for future missions to Jupiter (or Saturn). Experiments designed to measure such waves will need be even more sensitive than the URAP instrument (which is already greatly improved over past deep space missions).

4. The Jovian wave spectra are more or less smooth power laws. There are no spectral features that would indicate a particular instability. This is similar to the case for the Earth's BL waves.

5. The Jovian BL waves have been detected at ~noon and also at ~dusk, two different local time regions. It is therefore reasonable to assume that the waves are present at all local times. This would be the same as for the Earth's BL waves.

6. The ratio of B'/E' does not have a f^{-1} dependence, indicating that the waves may be interpreted as a mixture of electromagnetic and electrostatic emissions.

7. The Jovian BL wave intensities appear to be dependent on the external solar wind ram pressure. The waves are an order of magnitude more intense on the outbound leg where the ram pressure was typical for values at 5 AU (the pressure during the inbound leg was anomalously low). This is different than the Tsurutani et al. (1989) finding that the terrestrial wave intensities were independent of magnetosheath |B|.

8. Calculations indicate that 1-5 keV (and lower) electrons and 1-1,000 keV protons (and lower) are on strong pitch angle diffusion. We have determined that the 10-100 keV protons can contribute 0.85 ergs cm^{-2} sec^{-1} to the Jovian aurora. Extrapolation to 1 keV protons gives 6.9 ergs/ cm^{-2} s^{-1}, consistent with Hubble estimates of 8 ergs/cm^{-2} S-l.

9. The width of the Jovian aurora should be the width of he BL mapped down to he ionosphere. From Tsurutani et al. (1993), this should be ~100-200 km This is consistent with he Hubble UV measurements of Prange et al. (1995).

10. The location of the BL particle deposition will be at and inside the fool point of the last closed field line. If the BL waves at Jupiter are always present, as is the case at Earth, then one would expect a permanent auroral ring due to this mechanism. This same mechanism has been speculated to occur at Earth. A test of this hypothesis at Jupiter can be made by examining the depth of the aurora versus intensity. The numbers provided in this paper should be adequate to examine this possibility.

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Figure Captions

Figure 1. An overview of the low frequency E' and B' wave amplitudes for all fourteen BL events. The top four panels contain the spin plane average E', the next 4 the spin plane average B', the d.c. magnetometer variances, and the spacecraft location at the bottom. The BL events are shaded and numbered. Bow shock crossings are indicated by vertical dashed lines and magnetosheath/BL intervals by horizontal bars. The BL wave intensities were high on the

outbound pass when the solar wind ram pressure was more 11 OI'III2II (the rail) pressure was abnormally low on the inbound pass).

Figure 2. a) The power spectra of dc magnetometer for all fourteen BL intervals. b) The power law fits to the spectra. All spectra are similar in shape, varying primarily in intensity. The most intense intervals are events 8, 9 and 10.

Figure 3. The spectra for the URAP B' ELF waves. Note that almost all events are at 01" near instrumen t threshhold , except for a narrow region near 1-10117.

Figure 4. a) The electric (left panel) and magnetic (right pane]) wave spectra for event 9. The spectra are broadband with no obvious peaks. b) Same as in Figure 4 except for event lo. The wave power in both E' and B' arc highest in this event.

Figure 5. The low frequency end (d.c. magnetometer) of the magnetic spectrum for events 9 and 10. The VHM instrument noise level is indicated.

Figure 6. The combined MAG and URAP magnetic spectra for events 9 and 10. The d.c. power spectra are extrapolated to higher frequencies by dashed lines. The d.c. and a.c. magnetometer spectra join smoothly at ~1 Hz, as theoretically expected.

Figure 7. The ratio of E'/B' as a function of frequency. There is no f^{-1} dependence. It is speculated that the waves are a mixture of whistler mode plus electrostatic waves.

Figure 8. The electron spectra for event 10.

Figure 9. The ion (protons) spectra for event 10.

Figure 10. a) Plot across the southern hemisphere of Jupiter auroral oval on an image taken with the Faint Object Camera aboard HST on July 13, 1994. The filters used isolate the collisionally excited H2 Lyman bands around 1550 Angstroms. The counts are integrated along a north-south strip 40 pixels wide (~5000 km). The dashed line is a fit across another image at the same wavelength, but when the other side of the planet is facing the earth. It is used as a reference of the solar scattered flux from the planetary disc. One can note a region between the limb and the magnetic footprint of the orbit of Io, where there is an excess of emission from the aurorae. near the center of the auroral emission area, one can see the narrow bright auroral oval, b) Magnified

plot across the auroral oval with the background emission removed. Abscissa are pixel numbers toward the equator, ordinates are count-pix^{-1}.

'l'able Captions

Table 1. The 14 BL crossings identified by Phi llips et al . (1993). There are five crossings on the Ulysses inbound pass, days 33-35, 1992 and nine crossings on the outbound pass, days 43-45, 1992. The events have been numbered in chronological order for use of description.

Table 2. From left-to-right, particle species, resonant frequencies, wave power at the resonating frequencies, pitch angle diffusion rates, pitch angle scattering tim e-scales and bounce periods (assuming L = 60 magnetic field lines). -1 keV electrons are on strong diffusion. 1 () keV and higher energy protons are on strong diffusion.

Table 3. Energy deposition as function of species and energy ranges. The keV - 1 MeV protons can contribute 6.9 erg cm^{-2} s^{-1}. 1 - 5 keV electrons may reproduce the soft x-rays observed by EINSTEIN and ROSAT.

Table 4. A comparison of the Jovian BL plasma wave spectra and the Earth's wave spectra. The Ulysses spectra shapes are similar to the terrestrial cases.